



RESEARCH DEPARTMENT



REPORT

A wideband microstrip u.h.f. hybrid

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A WIDEBAND MICROSTRIP U.H.F. HYBRID
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Summary

The use of discrete power-splitting hybrids in u.h.f. circuit design can cause unnecessary mismatches and losses at connector junctions. A printed hybrid, with similar electrical characteristics, overcomes these problems and offers further savings of space and cost.

Tight coupling, however, is difficult to achieve in conventional microstrip construction. Also with tight coupling the velocity dispersion of coupled lines is more acute. Some ways of obtaining tight coupling and equalized phase velocities in printed couplers are outlined.

Two types of hybrid have been constructed: the 'overlay' and 'interdigitated' types. Measured characteristics are presented. The interdigitated hybrid has the more acceptable performance.

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Section	Title	Page
	Summary	Title Page
	List of Symbols	1
1.	Introduction	1
2.	Outline of requirements	2
3.	Techniques for achieving tight coupling in microstrip	2
	3.1. Tandem coupler	2
	3.2. Overlay coupler	2
	3.3. Podell coupler	2
	3.4. Interdigitated coupler	3
4.	Measured results	5
	4.1. Overlay coupler	5
	4.2. Interdigitated coupler	6
5.	Manufacture of interdigitated coupler	6
6.	Conclusions	6
7.	References	6
8.	Appendix	8

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A WIDEBAND MICROSTRIP U.H.F. HYBRID

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List of Symbols

c	free-space velocity of propagation of electromagnetic waves
d	coupled line separation, broadside configuration
E_r	electric field: r refers to a point of measurement
f	frequency
h	substrate board thickness
l	coupled line length
m, n, r	abbreviations defined in text
s	line gap
t	conductor thickness
v_{po}	odd-mode phase velocity of propagation
v_{pe}	even-mode phase velocity of propagation
w	line width
Z_o	general characteristic impedance
Z_{oe}	even-mode characteristic impedance of one line to earth
Z_{oo}	odd-mode characteristic impedance of one line to earth
δ	a function of line dimensions
Δ	board factor
ϵ_o	permittivity of free-space (8.854×10^{-12} F/m)
ϵ_r	relative permittivity
ϵ_r'	apparent relative permittivity
K	midband coupling
λ	wavelength
λ_g	guide wavelength
λ_{TEM}	wavelength, assuming pure TEM mode of propagation
P	output ratio
σ	a function of line dimensions
T	directivity

1. Introduction

An equal-power splitting hybrid, also called a 3 dB coupler, is a common component in u.h.f. circuit design. It is employed, for instance, as an aerial splitter or combiner, in balanced amplifiers, phase shifters, attenuators and modulators. A convenient form consists of two conducting lines, one quarter-wavelength long, with an earthed conductor wholly or partly surrounding them. (Fig. 11 in Section 8.1 defines the notation for terminal connections).

A discrete device, constructed in triplate, has been described in a previous report.¹ The cross-section of the lines in triplate form is shown in Fig. 1(a). The hybrid is wide-band, covering the u.h.f. Bands IV and V, has a directivity better than 25 dB and the ports are terminated in Type 'N' sockets.

A growing number of applications exist for a similar hybrid which can be directly printed on a low-loss, copper-clad laminate board like other r.f. components, e.g. amplifier modules and pin-diode assemblies. The advantages of this approach include the reduction of mismatch losses associated with cables and connectors, a saving of space and a reduction in cost. Microstrip technology — see Fig. 1(b) — whereby a pattern is printed on one side of the board and an earth plane on the reverse lends itself to such a design.² However, with this method of construction it is difficult to achieve the tight coupling required for a 3 dB coupler.

Section 3 presents several approaches to the design of a microstrip u.h.f. 3 dB coupler and describes in detail

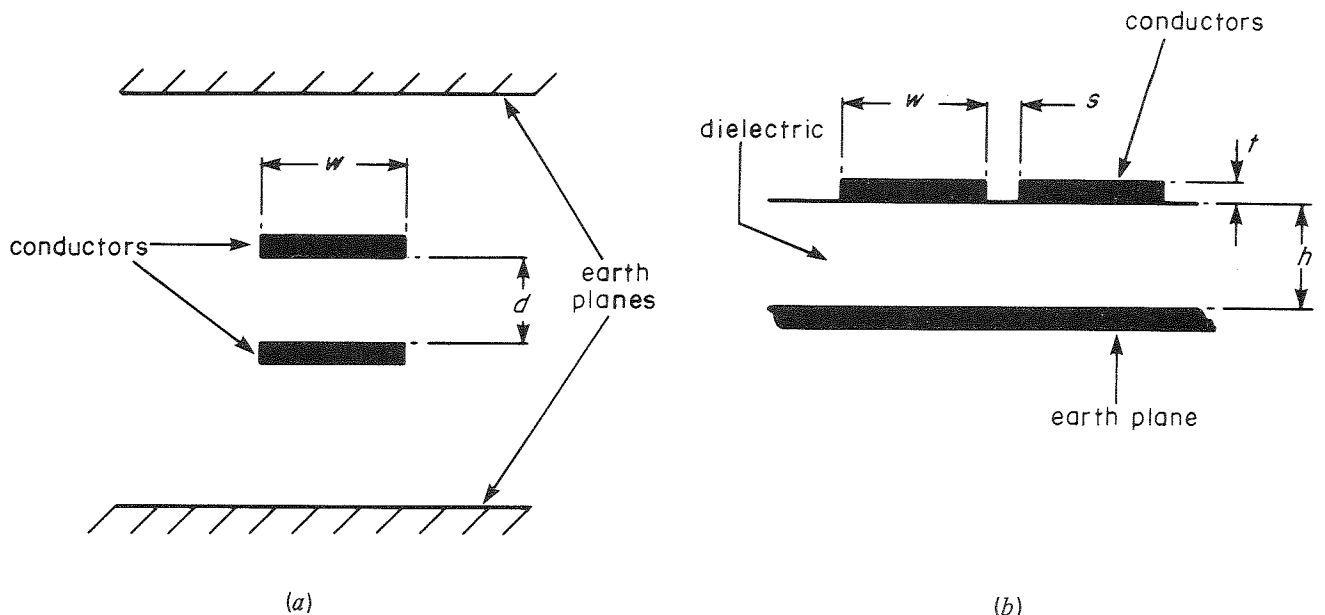


Fig. 1 - Methods of coupling lines
(a) triplate (b) microstrip

an interdigitated version. This latter design, which draws on computed data in the literature, has a similar electrical specification to the discrete device.

2. Outline of requirements

A coupler is conveniently analysed by superposition of its even- and odd-mode contributions: this means assessing separately the effect of driving the coupled lines in phase and antiphase respectively.^{3,4,11} The corresponding characteristic impedances can be written as $\frac{1}{2}Z_{oe}$ and $2Z_{oo}$ where the characteristic impedances of one line to earth for the two cases (referred to as the even-mode and odd-mode impedances) are Z_{oe} and Z_{oo} respectively. The required values are defined by the terminating port impedance and the amount of coupling required between lines. The impedance values themselves are controlled by the physical dimensions of the line configuration, e.g. line width, spacing etc.^{5,6,7,8}

For a 50Ω 3 dB coupler employing two-coupled lines, the values of Z_{oe} and Z_{oo} required are 120.7Ω and 20.7Ω respectively — see Appendix 8.2. In a triplate construction the physical dimensions required to achieve these impedances are of convenient size. In a microstrip construction the line separation becomes impracticably small, making tight coupling difficult to achieve.⁹

Another factor which complicates the design of microstrip couplers is the non-homogeneous nature of the dielectric.⁴ The even-mode field exists mostly in the base material with its high dielectric. Because the line spacing is small, field fringing at the line edges is small. The odd-mode field, however, is not confined to the base material and exists partly in the air above it. There is, therefore, a difference between the phase velocity associated with the odd and even modes: the tighter the coupling, the greater the dispersion. It is necessary to equalize the phase velocities to preserve directivity and bandwidth.

Matching at the terminating ports is important to preserve directivity and reduce losses.

The requirements of a microstrip 3 dB coupler design are, therefore:

- (a) A means of achieving tight coupling with practicable dimensions.
- (b) A means of minimizing the effects of dispersion.

Because the conductor dimensions affect both the characteristic impedance and velocities of propagation, the design requires a computer solution.¹⁰

3. Techniques for achieving tight coupling in microstrip

3.1. Tandem coupler

Two couplers can be connected in tandem to produce

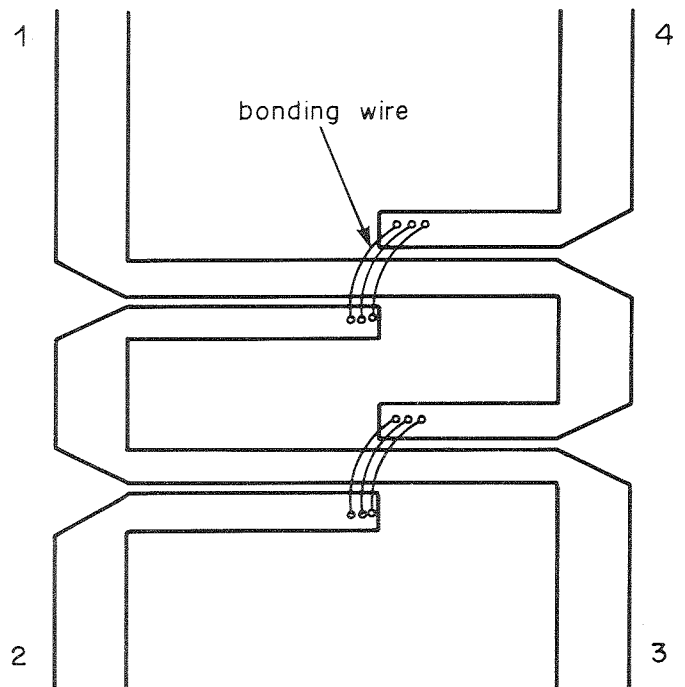


Fig. 2 - Couplers in tandem

an overall coupling which is greater than either individual one alone.¹¹ The etched pattern is shown in Fig. 2. This relieves, to some extent, the practical difficulty of etching a very narrow gap. Apart from the disadvantage of the extra space occupied by two couplers the bandwidth of the combination is less than either one alone.

3.2. Overlay coupler

By bridging the line gap with a 'floating' conductor the odd-mode impedance can be effectively reduced to tighten the coupling.^{4,12} Two arrangements are possible: either the extra conductor is printed on a subsidiary board mounted over the lines as in Fig. 3(a) or the earth plane is partially removed on the reverse-side of the main board and the extra conductor printed there — see Fig. 3(b). In the former approach the dielectric is effectively made more homogeneous by the addition of the extra board and this tends to equalize the velocities of propagation in the odd and even modes.

A coupler has been constructed of the form indicated in Fig. 3(b) and its performance is assessed in a later section.

3.3. Podell coupler

Although not applicable to a coupling as tight as 3 dB, this approach is included here for completeness because it offers a solution to the problem of dispersion.¹³ The even-mode field tends to propagate along the outer edges of a pair of coupled lines whilst the odd-mode field tends to

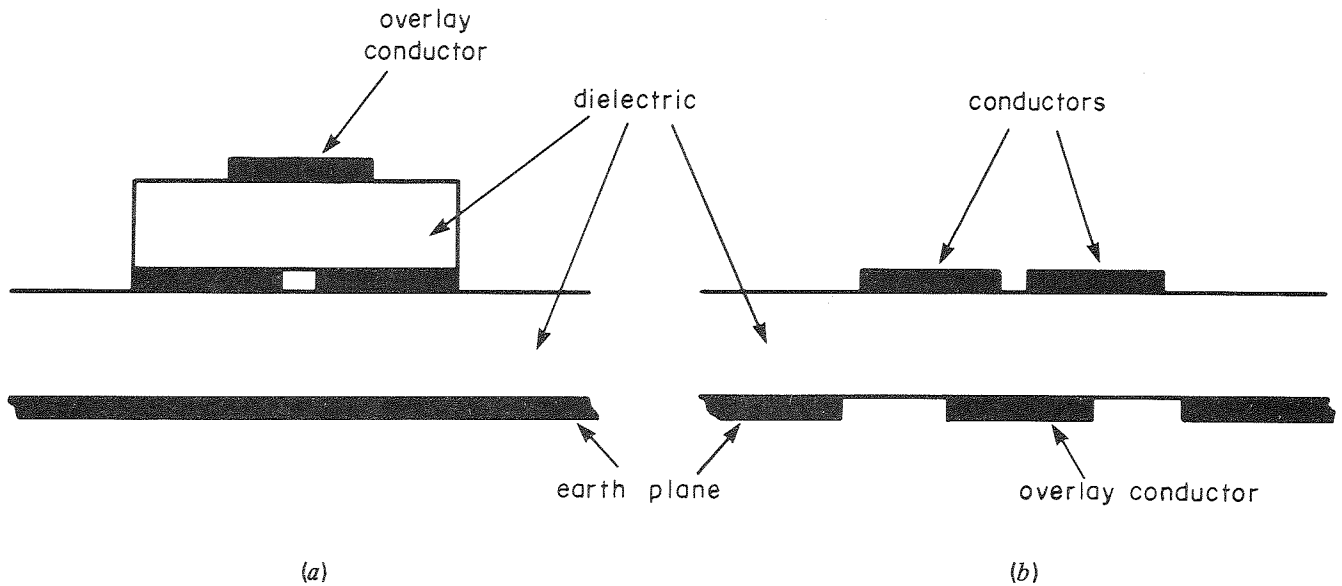


Fig. 3 - Overlay couplers
(a) ancillary board (b) broken earth plane

predominate along the inside edges. By printing the lines in a 'sawtooth' design as shown in Fig. 4 the odd-mode field can be slowed down because of the effectively longer path on the inside edges of the coupled lines. There must be a sufficient number of 'teeth' in the pattern to preserve the continuity of electrical performance across the frequency band. Coupling is limited to about 8 dB because of the practical etching tolerances in creating the line gap.

3.4. Interdigitated coupler

In this approach, more than two lines are printed and interconnected by bonding wires to produce two groups of coupled lines — see Fig. 5. Tighter coupling is possible with this arrangement — see Appendix 8.2. The even-mode field tends to be more in air in the region of the gaps

because of the greater fringing with the wider gaps. The odd-mode field is confined more to the dielectric, i.e. for the same degree of coupling the field in the air is less for an interdigitated coupler than a conventional coupler.

The Lange coupler was the first to use this principle.¹⁴ That design, however, had the output ports arranged as shown in Fig. 6. A later version proposed by Waugh and Lacombe had rearranged ports and fewer bonding wires.¹⁵

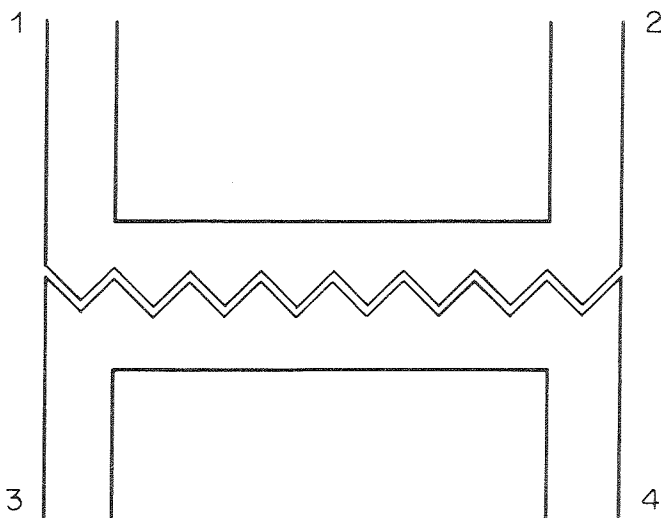


Fig. 4 - Podell coupler

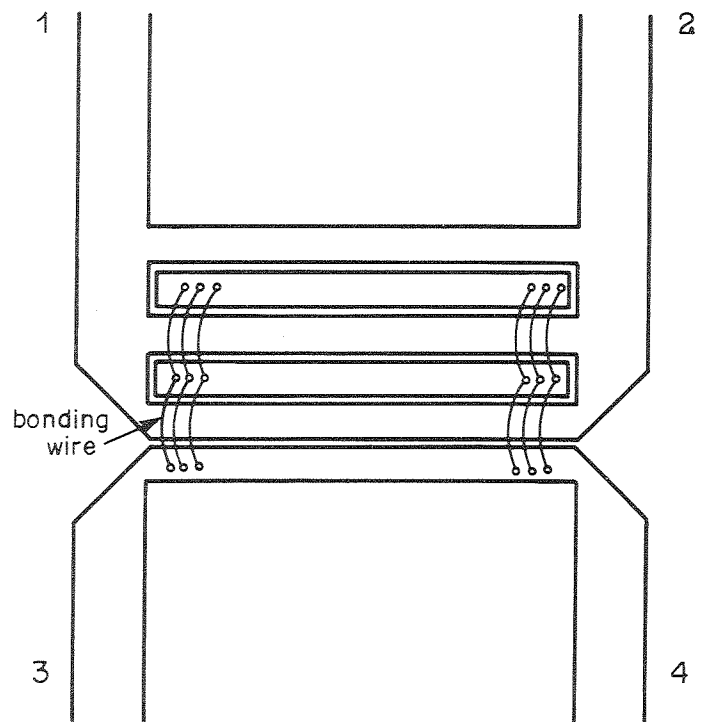
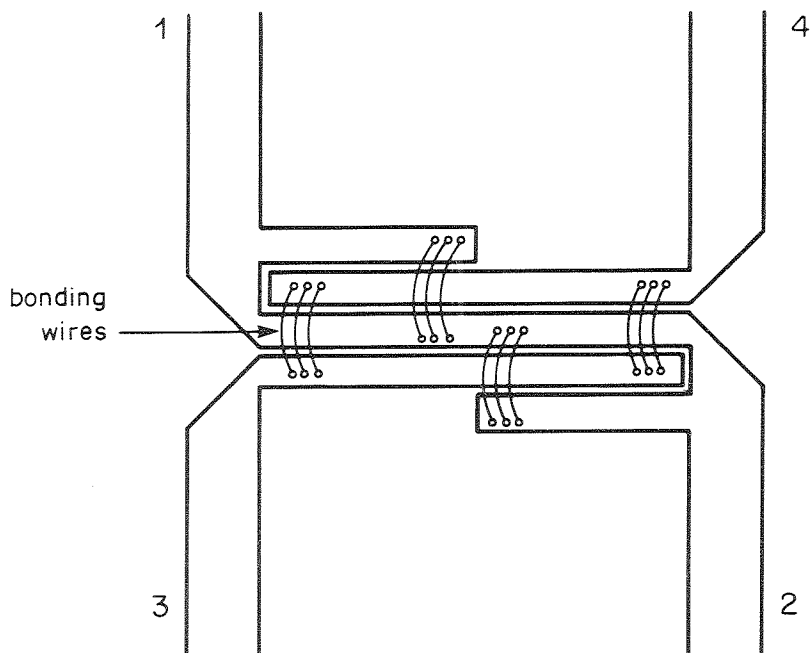


Fig. 5 - 6-line interdigitated coupler

Fig. 6 - Lange coupler



A coupler based on this approach has been designed for use at u.h.f. The arrangement is shown in Fig. 7. Four lines are used: this number appears to be optimum for this application because 6 lines would result in the line widths narrower than the gaps.¹⁶ Details of the design are presented in Appendix 8.3. The coupler length was chosen after measurement of the effective permittivity of the mixed dielectric and is based on a centre frequency of 650 MHz. The coupler, therefore, is designed to operate over the

whole u.h.f. television broadcasting band, 470 – 856 MHz. It is based on a low-loss, double sided copper-clad laminate with a dielectric thickness of 1.57 mm and copper thickness of 35 μm (Ashlam MG51). A photographic negative was produced from the original artwork at four-times full scale. Standard printed-circuit-board etching techniques were sufficient to produce the coupler. The wires, which are 12 μm diameter are hot-air soldered into position. The printed coupler, as constructed, is shown in Fig. 8.

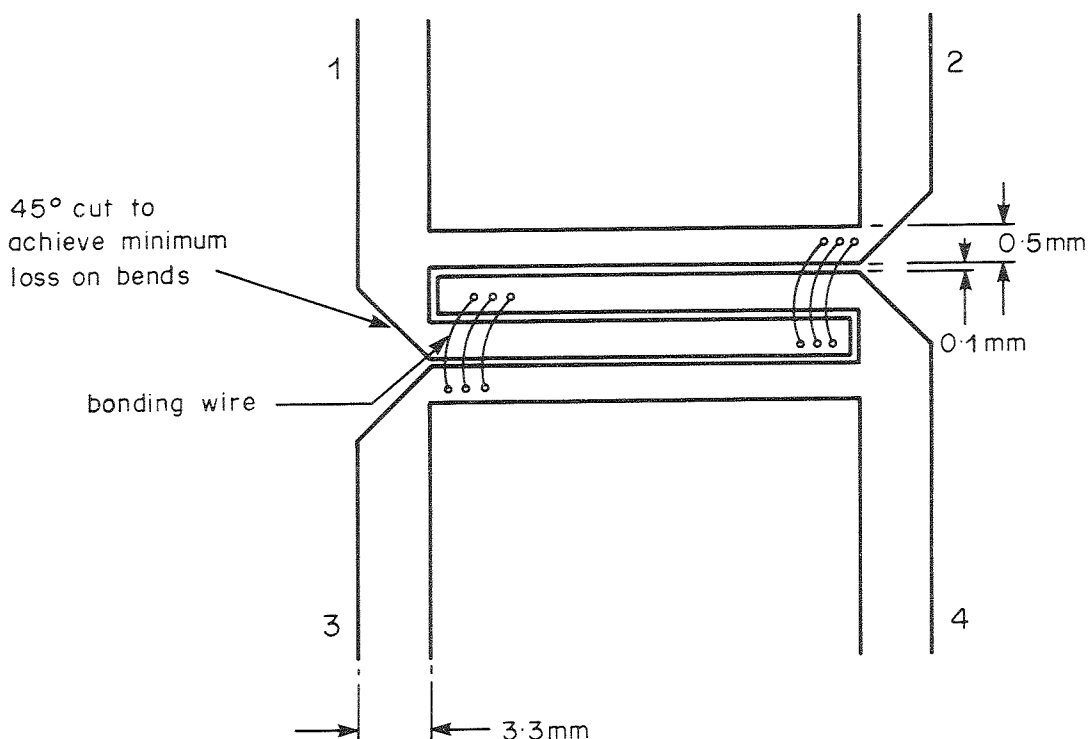


Fig. 7 - Design for u.h.f. interdigitated hybrid

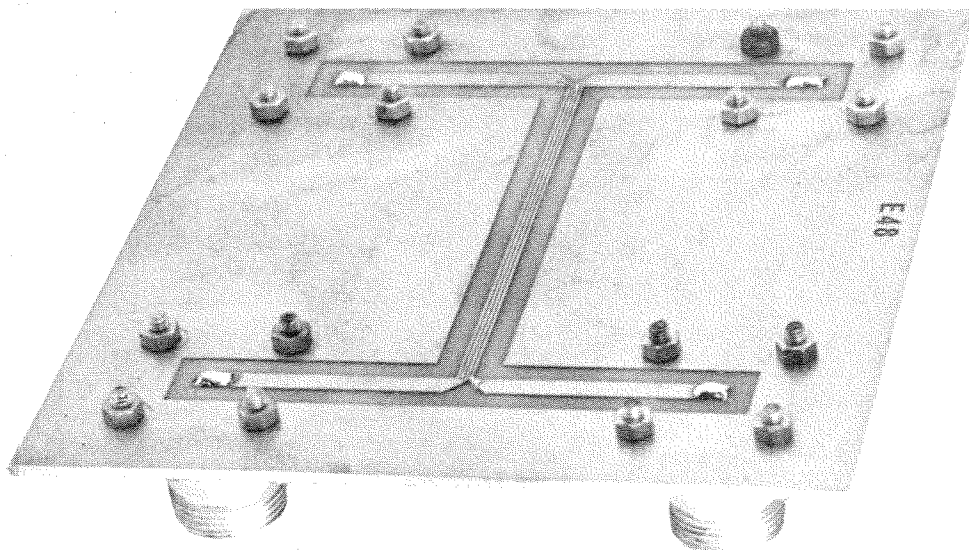


Fig. 8 - A u.h.f. interdigitated hybrid

4. Measured results

Prior to the interdigitated design a number of variations were built using the overlay technique and the results of the best of these are presented first.

4.1. Overlay coupler

The printed patterns of the coupler are given in Fig. 9. Although the tight coupling could be achieved over the whole band, the directivity and return losses at the ports

are poor. In the results which follow the direct coupling refers to the ratio of the signal power at the input to that at port 2 (see Fig. 11). The indirect coupling is the ratio of the signal power at the input to that at port 3.

Frequency of operation	: 470 – 856 MHz
Direct coupling	: 2.9 – 4.0 dB
Indirect coupling	: 3.0 – 4.0 dB
Directivity	: > 20 dB
Return loss	: > 14 dB

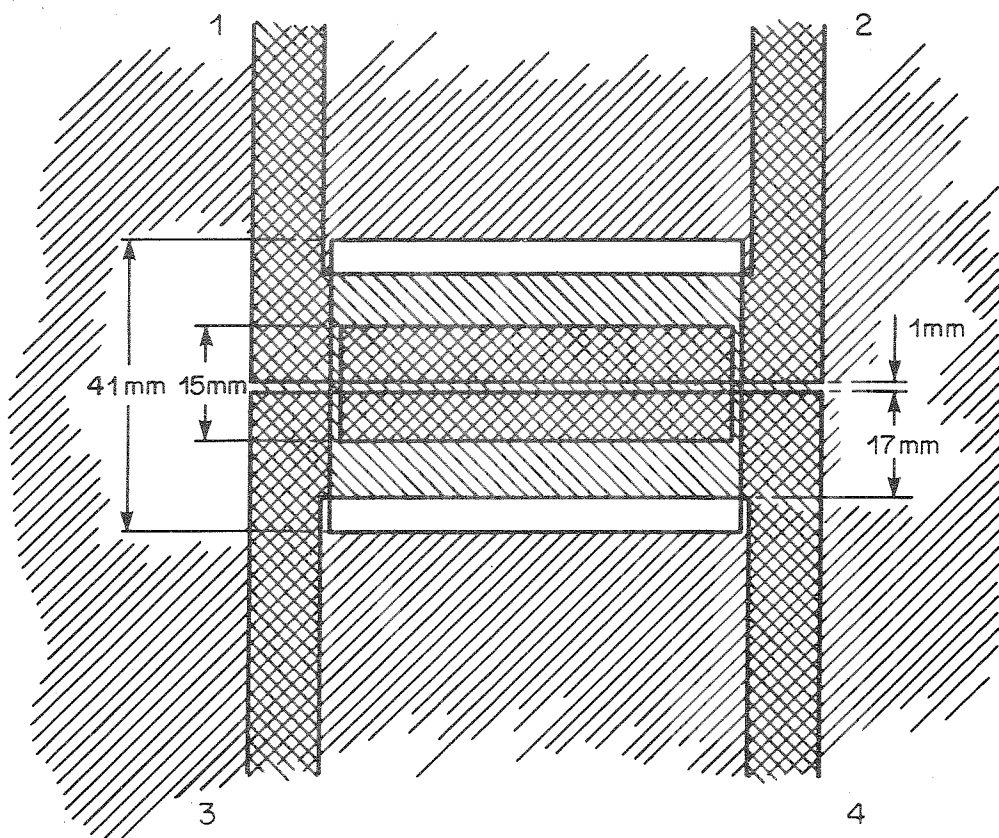
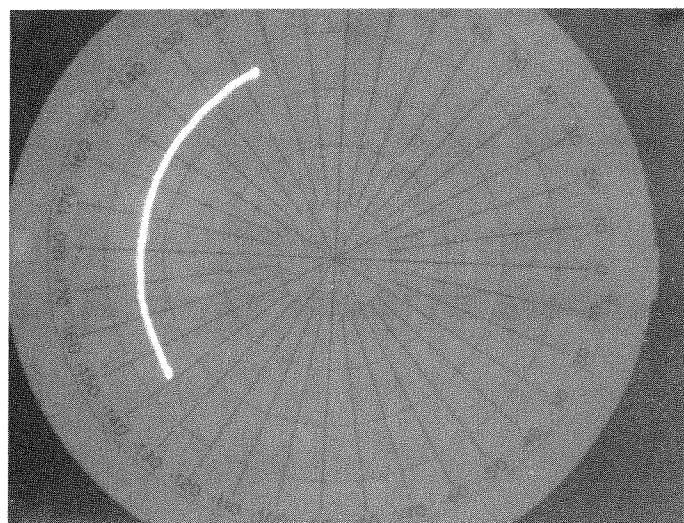
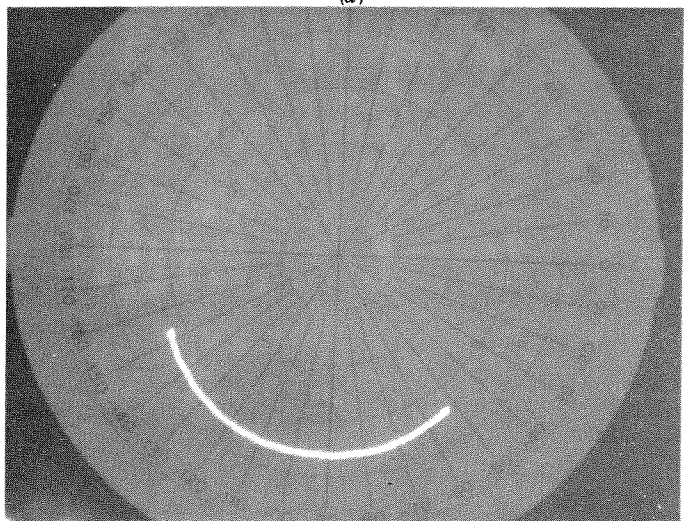


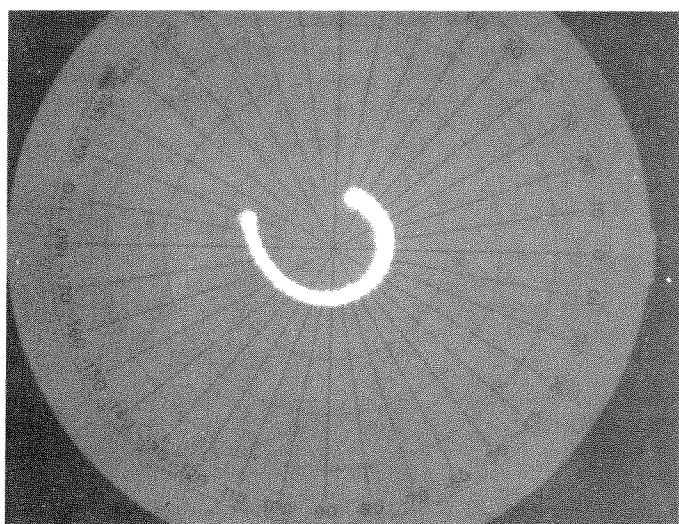
Fig. 9 - Overlay coupler
 \\\\\\\ top-side pattern
 ///// underside pattern



(a)



(b)



(c)

Fig. 10 - Measured characteristics of interdigitated hybrid, 470 – 856 MHz

- (a) Direct coupling response (0 dB full scale)
- (b) Indirect coupling response (0 dB full scale)
- (c) Isolated port response (–20 dB full scale)

4.2. Interdigitated coupler

The results of measurements made on a typical coupler built to the final design are given in Fig. 10 and the table below.

Frequency of operation	: 470 – 856 MHz
Direct coupling	: 2.9 – 3.5 dB
Indirect coupling	: 2.6 – 3.8 dB
Directivity	: > 27 dB
Return loss	: > 25 dB

It is estimated that a safe maximum operating power for these devices is 50W at 856 MHz (at an ambient temperature of 20°C). Under the normal operating condition dielectric heating is probably the limiting factor as far as power handling is concerned. One of the devices has been driven with 150W c.w. at 856 MHz for several minutes, with no apparent arcing but with considerable dielectric heating.

5. Manufacture of interdigitated coupler

The coupler artwork at four times full scale was produced on a precision cut-and-strip machine which has a linear resolution of better than 0.001 mm. A full-scale photographic negative produced from the artwork had the following measured linear tolerances.

Photographic negative	: line width 0.5 mm $\pm$ 0.01 mm
	: gap width 0.1 mm $\pm$ 0.01 mm
Overall mark-space ratio	: 5.0 $\pm$ 0.55

Following the etching process the mark-space ratio of the printed coupler is reduced to about 4.0 $\pm$ 0.5 because of undercutting. Out of a batch of five couplers, the mark-space ratio was measured as 3.84 $\pm$ 0.2.

The expected performance specification for couplers made to this design for the frequency range 470 to 856 MHz is as follows:

Coupling ratio	: 3 dB $\pm$ 0.8 dB
Directivity	: > 25 dB
Return loss	: > 25 dB (5.6%)

6. Conclusions

Some of the problems associated with producing tight coupling over a wide band using a microstrip configuration have been outlined. Of those considered, the most satisfactory design for a 3 dB coupler is based on an interdigitated approach. This design appears to be basically inexpensive and yet its electrical specification is similar to that for discrete devices in use to date.

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8. Appendix

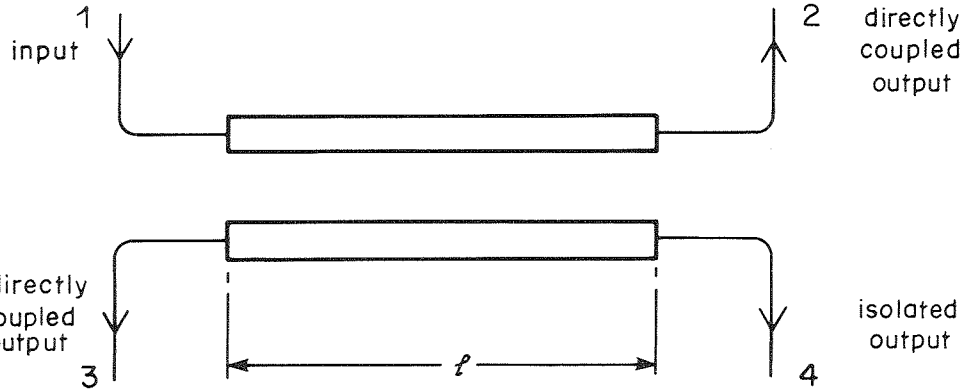


Fig. 11 - Basic coupler

8.1. Basic definitions

Let E_r be the field associated with the relevant numbered point referred to in Fig. 11. We define

$$\text{Output ratio, } P = \frac{E_3}{E_2} \quad (\text{i})$$

$$\text{Midband coupling, } K = \frac{E_3}{E_1} \quad (\text{ii})$$

$$\text{Directivity, } T = \frac{E_3}{E_4} \quad (\text{iii})$$

For an equal-power splitting hybrid, the theoretical values of the above for $l = \lambda/4$ and matched conditions are:

$$\left. \begin{array}{l} P = 0 \text{ dB} \\ K = -3 \text{ dB} \\ T = \infty \end{array} \right\}$$

Over the active bandwidth, P varies sinusoidally with frequency and reaches a maximum when $l = \lambda/4$. The output at port (3) leads the output at port (2) by 90° .

It is convenient to analyse the coupler behaviour in terms of odd and even mode excitation.

We define the odd mode and even mode characteristic impedances Z_{oo} and Z_{oe} where:¹

Z_{oo} is the characteristic impedance of a single line to earth when driven in the odd mode.

Z_{oe} is the characteristic impedance of a single line to earth when driven in the even mode.

For matched conditions

$$Z_o^2 = Z_{oo} Z_{oe} \quad (\text{iv})$$

where σ is a function of the line dimensions.

$$Z_{oo} = Z_o \sqrt{\frac{1-K}{1+K}} \quad (\text{v})$$

$$Z_{oe} = Z_o \sqrt{\frac{1+K}{1-K}} \quad (\text{vi})$$

Re-arranging,

$$K = \frac{\frac{Z_{oe}}{Z_{oo}} - 1}{\frac{Z_{oe}}{Z_{oo}} + 1} \quad (\text{vii})$$

Also we define a guide wavelength, λ_g , where

$$\lambda_g = \frac{c}{f} \cdot \Delta \quad (\text{viii})$$

where c is the free space propagation velocity
 f is the centre frequency

Δ is the board factor to take account of the non-homogeneous medium.

To a first approximation Δ is given by,

$$\Delta \doteq \frac{1}{\sqrt{\frac{1+\epsilon_r}{2}}} \quad (\text{ix})$$

but because Δ depends also on the final line dimension it is more accurately written:⁶

$$\Delta = \frac{1}{\sqrt{\frac{1+\epsilon_r}{2} (1+\sigma)}} \quad (\text{x})$$

Alternatively,⁹

$$\Delta = \frac{1}{\sqrt{1 + \delta^2 (\epsilon_r - 1)}} \quad (\text{xi})$$

where ϵ_r is the relative permittivity of the board and δ is a function of the line dimensions.

8.2. Line impedances for interdigitated structures

For couplers constructed from more than two lines, the lines are interdigitated and connected alternately. The lines for each coupler are the same width: likewise, the gaps between lines. The values of Z_{oo} and Z_{oe} quoted in the following table for these multiline structures are the odd- and even-mode impedances for any adjacent pair of lines in the absence of all others.¹⁶ They represent the impedance required in the design in order to achieve the coupling given in the second column. In the calculation the following assumptions apply:

- the coupling between non-adjacent lines is negligible
- propagation is TEM
- the terminating impedances are matched to the coupler.

Number of lines	K (dB)	$Z_{oo}(\Omega)$	$Z_{oe}(\Omega)$
2	-3	20.71	120.70
	-6	28.87	86.60
	-10	36.04	69.37
4	-3	52.61	176.20
	-6	67.96	142.50
	-10	76.30	118.30
6	-3	82.55	243.10
	-6	105.10	204.30
	-10	122.10	181.10

8.3. Design of interdigitated coupler

8.3.1. Design procedure

The design falls conveniently into four parts:

- For a given value of coupling ratio, K , the number of lines to use and the respective values of Z_{oo} and Z_{oe} are obtained from the Table in Appendix 8.2. The choice of the number of lines ultimately depends on the kind of geometry obtained from the relevant impedances. Some choices will give very narrow gaps, e.g. two lines for $K = -3$ dB; others will give very narrow lines.
- From the odd- and even-mode impedances, two single-line shape ratios are found corresponding to $Z_{oo}/2$ and $Z_{oe}/2$. They are $\frac{w}{h}/_{se}$ and $\frac{w}{h}/_{so}$ respectively.¹⁰ Theoretical curves³ are available for obtaining these or alternatively the following expression may be used:—

$$\frac{w}{h}/_s = \frac{2}{\pi}(r-1) - \frac{2}{\pi}\ln(2r-1) + \frac{\epsilon_r-1}{\pi\epsilon_r}\left[\ln(r-1) + 0.293 - \frac{0.517}{\epsilon_r}\right] \quad (\text{xii})$$

$$\text{where } r = \frac{60\pi^2}{Z_o\sqrt{\epsilon_r}} \quad (\text{xiii})$$

- From the values of $\frac{w}{h}/_{se}$ and $\frac{w}{h}/_{so}$ the values of $\frac{w}{h}$ and $\frac{s}{h}$ which describe the line geometry can be found by simultaneous solution of the following formulae.⁹

$$\frac{w}{h}/_{se} = \frac{2}{\pi} \cosh^{-1} \left(\frac{2n - m + 1}{m + 1} \right) \quad (\text{xiv})$$

$$\frac{w}{h}/_{so} = \frac{2}{\pi} \cosh^{-1} \left(\frac{2n - m - 1}{m - 1} \right) + \frac{4}{\pi \left(1 + \frac{\epsilon_r}{2}\right)} \cosh^{-1} \left(1 + 2 \frac{w/h}{s/h} \right) \quad (\text{xv})$$

$$\text{where } m = \cosh \left(\frac{\pi}{2} \cdot \frac{s}{h} \right)$$

$$n = \cosh \left(\pi \cdot \frac{w}{h} + \frac{\pi}{2} \cdot \frac{s}{h} \right)$$

- The line lengths are determined initially from (viii) and (ix). Because the board has first to be made before Δ can be measured accurately, a more accurate line length is found using (x) or (xi).

8.3.2. Example: 3 dB coupler for Bands IV and V

- For 4 lines, 3 dB coupling

$$Z_{oo} = 52.61\Omega$$

$$Z_{oe} = 176.20\Omega$$

- For $Z_{oe}/2 = 88.10\Omega$ and $Z_{oo}/2 = 26.30\Omega$, the values of the single-line shape ratios are

$$\frac{w}{h}/_{se} = 0.7$$

$$\frac{w}{h}/_{so} = 5.4$$

- Simultaneous solution of (xiii) and (xiv) gives

$$\frac{w}{h} = 0.32$$

$$\frac{s}{h} = 0.07$$

For a coupler made from a double-sided copper-clad laminate, MG51 ($h = 1.5$ mm)

$$w = 0.5 \text{ mm}, \quad s = 0.1 \text{ mm}$$

(d) From (viii),

$$l = \frac{\lambda_g}{4} = \frac{1}{4} \cdot \frac{c}{f} \cdot \Delta$$

Also from (ix), to a first approximation: $\Delta \div \frac{1}{\sqrt{\left(\frac{1+\epsilon_r}{2}\right)}}$

For MG51, $\epsilon_r = 3.7$,

$$\Delta = 0.65$$

$$\therefore l = \frac{1}{4} \times \frac{3 \times 10^8}{650 \times 10^6} \times 0.65 = \underline{75.3 \text{ mm}}$$

8.3.3. Measurements on coupler constructed

After etching, the average line-widths and gap-widths were measured to be

$$w = 0.48$$

$$s = 0.12 \text{ mm}$$

For MG51

$$\frac{w}{h} = 0.306, \quad \frac{s}{h} = 0.076$$

From Equations (xiv) and (xv), these give

$$\frac{w}{h} \bigg|_{se} = 0.68, \quad \frac{w}{h} \bigg|_{so} = 5.04$$

$$\therefore r_e = 3.47, \quad r_o = 11.05$$

$$\therefore \underline{Z_{oe} = 178\Omega}, \quad \underline{Z_{oo} = 56\Omega}$$

From measurements of coupling ratio, the optimum coupler length for Bands IV and V is found to be 73.5 mm.

This implies that from Equation (x)

$$\Delta = \frac{1}{\sqrt{\frac{1+\epsilon_r}{2} (1+\sigma)}}$$

$$\underline{\sigma = 0.0451}$$